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Phytosociology of *Capparis decidua* (Forssk.) Edgew inhabiting Wadi Tundoub, Southern Eastern Desert, Egypt

Fawzy M. Salama[1], Noha A. El-Tayeh[2], Hana K. Galal[1] , Asmaa M. Sayed[1,*] and Ali E. Gaafar[3]

1; Botany & Microbiology Department, Faculty of Science, Assiut University, Egypt
2; Botany and Microbiology Department, Faculty of Science, (Qena) South Valley University, Egypt.
3; Botany and Microbiology Department, Faculty of Science, New Valley University, El Kharga,71511 Egypt.

*Corresponding Author: asmaa.mahmoud9115@gmail.com

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ABSTRACT

This study investigates the phytosociology of *Capparis decidua* within Wadi Tundoub, located in Egypt's Eastern Desert, focusing on its distribution and ecological adaptations in hyper-arid conditions. The research surveyed 64 plant species across 27 stands, identifying 17 annuals and 47 perennials from 22 families, including Fabaceae, Zygophyllaceae, and Amaranthaceae. Using TWINSPAN and Redundancy Analysis (RDA), the vegetation was classified into four distinct groups, each influenced by soil properties such as sand, clay, and mineral content. *Capparis decidua* emerged as the dominant species, exhibiting its resilience and adaptability to the extreme desert environment. The associated flora reflects a xerophytic composition, with life forms predominantly consisting of chamaephytes and therophytes, adapted to arid ecosystems. Chorological analysis revealed a strong representation of Saharo-Arabian elements, emphasizing the biogeographical affinities of the studied flora. The findings highlight significant correlations between vegetation patterns and soil variables, such as coarse sand, clay, K, and CO_3 concentrations, which influence species distribution. This study enhances the understanding of vegetation dynamics in Egypt's hyper-arid regions, providing valuable insights for biodiversity conservation and sustainable land management. The adaptability of *C. decidua* and its associated flora underscores the ecological importance of wadis as reservoirs of biodiversity in desert ecosystems.

INTRODUCTION

Capparis decidua (Forssk.) Edgew., commonly known as the desert caper, is a drought-tolerant shrub in the Capparaceae family, primarily distributed across arid and semi-arid regions of North Africa, the Middle East, and South Asia [1,2]. This species, native to desert landscapes, plays a crucial ecological role in stabilizing the soil, preventing erosion, and contributing to biodiversity in extreme environments. In Egypt, *Capparis decidua* is predominantly found in the Eastern Desert, where it thrives in ephemeral watercourses known as wadis. These regions, characterized by harsh climatic conditions and limited water availability, support a variety of xerophytic species that are well adapted to surviving in environments with extreme temperature fluctuations, low rainfall, and poor nutrient availability [3,4].

The Eastern Desert of Egypt represents a vast, hyper-arid ecosystem that spans approximately 223,000 km² and is largely characterized by rocky and sandy terrains, minimal rainfall, and high-temperature variations [5]. Despite these extreme conditions, the Eastern Desert supports a diverse range of plant species, many of which are adapted to the highly variable water availability in Wadis. These temporary riverbeds, which capture and retain water from rare rainfall events, serve as critical habitats for a wide range of flora, including *Capparis decidua* [6]. The presence of *Capparis decidua* in these ecosystems highlights its resilience and the unique ecological adaptations that enable it to thrive in such challenging environments [7].

Capparis decidua is not only ecologically significant but also holds considerable ethnobotanical value. The plant has been used for centuries in traditional medicine, especially for its anti-inflammatory, antimicrobial, and hepatoprotective properties. It is also a source of food, with its fruits consumed both fresh and in processed forms, such as pickles and jams [8]. Furthermore, the species is utilized in afforestation and land reclamation projects due to its ability to survive under extreme drought conditions and contribute to soil stabilization, making it an essential species for combating desertification in arid regions [2,4].

Wadi Tundoub, located in the southern part of the Eastern Desert, serves as a unique study area for examining the phytosociology and ecological dynamics of desert flora. This wadi is an important hydrological feature that temporarily retains water after rare rainfall events, creating a habitat for plants such as *Capparis decidua* that are adapted to survive in arid environments. Despite the infrequency of rainfall, the ephemeral nature of water availability in the wadi is crucial for the persistence of species that rely on intermittent moisture sources for growth [3]. Vegetation surveys in the Eastern Desert, particularly in the wadis, have revealed that plant communities are highly adapted to the region's nutrient-poor soils and low moisture availability. The vegetation is often dominated by xerophytic species, including *Capparis decidua*, which exhibit traits such as deep root systems, specialized leaf structures, and water-conserving mechanisms that enable them to survive prolonged dry periods [9,3]. The vegetation in these environments is typically composed of chamaephytes, therophytes, and a few perennial species that can tolerate the region's extreme environmental conditions [4,9].

The phytosociological characteristics of *Capparis decidua* in Wadi Tundoub provide a valuable case study for understanding how desert plants adapt to a variety of environmental gradients. Vegetation patterns in desert ecosystems are often strongly influenced by soil properties, water availability, and climatic conditions, which can vary substantially across short distances [7]. Thus, this study aims to assess the distribution of *Capparis decidua* concerning key soil factors such as sand, clay, and mineral content, while also investigating its ecological interactions with other plant species in the area.

This research further explores the role of *Capparis decidua* in the broader ecological context of the Eastern Desert, focusing on the relationships between vegetation and environmental variables. By using advanced multivariate techniques, including TWINSPAN and Redundancy Analysis (RDA), the study will classify the plant communities in Wadi Tundoub based on their species composition and environmental characteristics. This will help to identify the key soil factors influencing the distribution of *Capparis decidua* and other co-occurring species, thus contributing to a better understanding of the ecological processes governing desert vegetation dynamics [10,3].

Ultimately, this study aims to enhance our understanding of how *Capparis decidua* and other desert plants adapt to extreme environmental conditions, providing insights that could inform conservation strategies, land reclamation efforts, and sustainable management practices for arid regions. Given the increasing pressures of climate change and human activity on desert ecosystems, understanding the resilience and adaptability of such species is crucial for preserving biodiversity and maintaining ecosystem services in these fragile environments [11,12].

MATERIALS AND METHODS

Study Area

The study was conducted in Wadi Tundoub, situated in the southern portion of the Eastern Desert of Egypt, approximately 20 km south of Quseir City along the Red Sea coast (25° 55' N to 25° 59' N latitude and 34° 11' E to 34° 23' E longitude) [3,13]. This region is characterized by hyper-arid conditions (Figure 1), with minimal rainfall, high temperatures, and significant seasonal variability in humidity [3,5]. The geology of Wadi Tundoub is primarily composed of Dokhan volcanic rocks, including andesites and dacites, and wadi-bed sediments that serve as temporary reservoirs for water during rare rainfall events. These sediments, including coarse sands and gravels, facilitate the temporary storage of runoff water which sustains vegetation growth [14].

Figure (1) Map of the area investigated.

Soil Analysis

Soil samples were systematically collected from 27 stands within Wadi Tundoub, where Capparis decidua was present. The selected stands, each approximately 25×25 m in area, represent the vegetation zones that support Capparis decidua. At each stand, four composite soil samples were taken at depths of 0–25 cm, mixed thoroughly, and air-dried for further analysis.

Soil Texture and Composition:

Soil texture was determined using the standard mechanical separation method of pipette and sieve analysis [15]. The sand, silt, and clay proportions were calculated to describe the soil texture at each stand.

Soil Chemical Properties:

Soil water extracts were prepared by mixing soil with distilled water in a 1:5 ratio, and the pH was measured using a pH meter following the method described by [16]. Electrical conductivity (EC) and total soluble salts (TSS) were measured using a conductivity meter as outlined by [16]. Soluble cations, including sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg), were quantified using a flame photometer [17], while anions such as chlorides (Cl) and sulfates (SO_4) were analyzed using the methods described by [18]. Total carbonates (CO_3) were measured according to [16], and phosphates (PO_4) were assessed using Vogler's method [19].

Floristic Analysis

Field Survey:

Floristic surveys were conducted in 2021 and 2022 in the study area. During these surveys, both annual and perennial species associated with Capparis decidua were recorded. The identification and classification of plant species followed the taxonomy provided by [20] and [21,22]. All identified species were collected, with voucher specimens deposited in the Assiut University Herbarium (ASU).

Life Form Classification:

The life forms of plant species were categorized based on [23] classification, which divides plants into different life forms based on their survival strategies in response to environmental stressors. These life forms include therophytes (annuals), chamaephytes (shrubs), phanerophytes (trees), geophytes (plants that regenerate from underground storage organs), and hemicryptophytes (plants with buds located just above the soil surface).

Phytogeographical Distribution:

The phytogeographical analysis of species was conducted according to the chorological systems of [24,20]. Species were classified into different chorotypes based on their distribution patterns, which reflect their biogeographical origins. The distribution was analyzed using a combination of floristic data and historical biogeographical studies to assess the degree of species affinity to various regional flora.

Data Collection

A total of 27 stands were selected based on the presence of *Capparis decidua*, and their vegetation characteristics were surveyed. Each stand covered an area of approximately 25×25 m, which is considered the minimum size for representative plant communities. Field data collection involved recording the species' presence or absence in each stand, and presence percentages (P%) were calculated to estimate the species richness and diversity at each location.

Multivariate Data Analysis

TWINSPAN Classification:

To analyze vegetation patterns and classify the species into distinct vegetation groups, the Two-Way Indicator Species Analysis (TWINSPAN) method was used [25]. This hierarchical classification technique simultaneously organizes both stands and species into clusters based on their similarities. It creates a two-way table that highlights the relationships between species and environmental variables, helping to identify indicator species for each vegetation group.

Ordination Techniques:

For ordination analysis, we used CANOCO [26] to perform Detrended Correspondence Analysis (DCA) and Redundancy Analysis (RDA). DCA was initially applied to evaluate the variation in species composition across stands, identifying gradients of species diversity. The first and second DCA axes explained a significant proportion of the variation in floristic data [27]. Following DCA, RDA was employed to assess the relationships between species composition and environmental variables, such as soil pH, EC, TSS, and nutrient concentrations [28]. RDA biplots were used to visualize the association between soil factors and plant species distributions.

Statistical Analysis

Soil variables among the different vegetation groups identified by TWINSPAN were compared using one-way ANOVA, and statistical significance was assessed using F-tests at $p < 0.05$. Diversity indices, such as the Shannon-Wiener diversity index (H') and species richness (SR), were calculated for each vegetation group to evaluate the biodiversity within the stands. These indices help quantify the degree of species diversity in different vegetation communities and were computed according to the methods outlined by [29].

RESULTS

Floristic Composition and Species Diversity

The floristic survey of Wadi Tundoub recorded a total of 64 plant species, which were classified into 51 genera and 22 families (Table 1). The most species-rich families were Fabaceae, with 13 species, followed by Zygophyllaceae (9 species) and Amaranthaceae (6 species). Families with significant representation also included Brassicaceae and Resedaceae, each with four species. Additionally, Boraginaceae, Apocynaceae, and Cleomaceae contributed three species each. Families such as Poaceae, Asteraceae, Polygonaceae, Capparaceae, and Caryophyllaceae each had two species, while Cucurbitaceae, Euphorbiaceae, and Solanaceae each had one species.

Table (1): Species composition of the study area in Wadi Tundoub classified according to the different families, together with their chorology types. Coro= Chorology type (SA= Saharo-Arabian, SZ= Sudano-Zambezian, M= Mediterranean, IT= Irano-Turanian, GC= Gueno-Cungo, and SU= Sudanian. LF = Life forms (Th: Therophytes, H: Hemicryptophytes, Ch: Chamaephytes, G: Geophytes, and Ph: Phanerophytes, P: Parasite and Dur = Duration (Ann: Annual, Per: Perennial), P% = presence value.

Families and species	Dur	Coro	L.F	P%
Amranthaceae				
Aerva javanica (Burm.f.) Juss. ex Schult.	Per	SA	Ch	33.3
Anabasis articulata (Forssk.) Moq.	Per	SA	Ch	14.8
Atriplex halimus L.	Per	SA	Ch	18.5

Caroxylon gaetulum (Maire) Akhani & Roalson	Per	SA+SZ	Ch	18.5
Cornulaca monacantha Delile	Per	SA	Ch	11.1
Haloxylon salicornicum (Moq.) Bunge ex Boiss.	Per	SA+IT	Ch	11.1
Apocynaceae				
Leptadenia pyrotechnica (Forssk.) Decne.	Per	SA+SZ	Ph	44.4
Pergularia tomentosa L.	Per	SA	Ch	11.1
Solenostemma oleifolium (Nectoux) Bullock & E.A. Bruce ex Maire	Per	SA	Ph	18.5
Asteraceae				
Launaea spinosa (Forssk.) Sch. Bip. ex Kuntze	Per	SA	Ch	37
Pulicaria undulata (L.) C. A. Mey	Per	SA	H	33.3
Boraginaceae				
Arnebia hispidissima (Lehm.) A. DC.	Ann	SA	Th	25.9
Anchusa aegyptiaca (L.) A. DC.	Ann	SA	Th	22.2
Trichodesma africanum (L.) Sm.	Ann	SA+SZ	Th	25.9
Brassicaceae				
Eremobium aegyptiacum (Spreng.) Asch. ex Boiss.	Per	SA	H	22.2
Farsetia aegyptia Turra	Per	SU	Ch	25.9
Lobularia arabica (Boiss.) Muschl.	Ann	SA	Th	25.9
Zilla spinosa (L.) Prantl	Per	SA	Ch	74.1
Cappariaceae				
Capparis decidua (Forssk.) Edgew.	Per	SA+SU	Ph	100
Capparis spinosa L.	Per	M+SA+IT	Ch	3.7
Caryophyllaceae				
Polycarpaea repens (Forssk.) Asch. & Schweinf.	Per	SA	Th	25.9
Pteranthus dichotomus Forssk.	Ann	SA	Th	29.6
Cleomeaceae				
Cleome amblyocarpa Baratte. & Murb.	Ann	SA	Th	29.6
Cleome arabica L.	Per	SU	Ch	11.1
Cleome droserifolia (Forssk.) Delile	Per	SA+IT	H	37
Cucurbitaceae				
Citrullus colocynthis (L.) Schrad.	Per	M+SA+IT	H	22.2
Euphrbiaceae				
Chrozophora oblongifolia (Delile) A.Juss. ex Spreng.	Per	M+SA	Ch	14.8
Fabaceae				
Alhagi graecorum Boiss.	Per	ME+IT	H	14.8
Astragalus hamosus L.	Ann	M+IT	Th	11.1
Astragalus sieberi DC.	Per	SA	Ch	7.4
Astragalus vogelii (Webb) Bornm.	Ann	SA	Th	11.1
Blepharis ciliaris (L.) B.L.Burtt	Per	SA	H	11.1
Crotalaria aegyptiaca Benth.	Per	SZ	Ch	18.5
Lotononis platycarpa (Viv.) Pic.Serm.	Ann	SA+SU	Th	11.1
Lotus hebranicus Brand	Per	M	H	7.4
Retama raetam (Forssk.) Webb	Per	SA+IT	Ph	25.9
Senna italica Mill.	Per	SA+SZ	Ch	18.5

Vachellia seyal (Delile) P.J.H. Hurter	Per	SU	Ph	14.8
Vachellia tortilis (Forssk.) Galasso & Banfi subsp. raddiana	Per	SA+SZ	Ph	44.1
Vachellia tortilis (Forssk.) Galasso & Banfi	Per	SA+SZ	Ph	29.6
Geraniaceae				
Erodium glaucophyllum (L.) L'Hér.	Per	SA	H	11.1
Liliaceae				
Asphodelus tenuifolius Cav.	Ann	M+SA+IT	Th	11.1
Moringaceae				
Moringa peregrina (Forssk.) Fiori	Per	SZ+GC	Ph	3.7
Orobanchaceae				
Orobanche crinita Viv.	Ann	M+SA+IT	P	3.7
Plumbaginaceae				
Limonium axillare (Forssk.) Kuntze	Per	SA	H	11.1
Poaceae				
Panicum turgidum Forssk.	Per	M+SA	G	11.1
Stipagrostis plumosa Munro ex T.Anderson	Per	M+SA+IT	H	11.1
Polygonaceae				
Calligonum comosum L.'Her.	Per	SA+IT	Ph	11.1
Rumex vesicarius L.	Ann	ME+SA+IT	Th	18.5
Resedaceae				
Caylusea hexagyna (Forssk.) M.L. Green	Ann	SA	Th	14.8
Ochradenus baccatus Delile	Per	SA	Ph	66.7
Reseda alba L.	Ann	M+IT	Th	14.8
Reseda pruinosa Delile	Ann	SA	Th	18.5
Solanaceae				
Hyoscyamus boveanus (Dunal) Asch. & Schweinf.	Per	SA	H	14.8
Urticaceae				
Forsskaolea tenacissima L.	Per	SA+SZ	H	14.8
Zygophyllaceae				
Balanites aegyptiaca L.	Per	SA+SZ	Ph	11.1
Fagonia arabica L.	Per	SA	Ch	14.8
Fagonia glutinosa Delile	Per	SA	H	25.9
Fagonia indica Burm.f.	Per	SA	Ch	18.5
Fagonia mollis Delile	Per	SA	Ch	22.2
Tribulus pentandrus Forssk.	Ann	SU	Th	18.5
Zygophyllum album L.	Per	M+SA+IT	Ch	11.1
Zygophyllum coccineum L.	Per	SA	Ch	33.3
Zygophyllum simplex L.	Ann	SA+SZ	Ch	14.8

Life Forms and Chorological Affinities

Life form

The life forms of the recorded plant species in Wadi Tundoub were classified according to Raunkiaer's system. Chamaephytes dominated, reflecting the adaptation of most species to the arid conditions, where drought resistance is crucial for survival (Table 1). Therophytes were the second most common life form, indicating a high proportion of annual species that complete their life cycles during the brief periods of water availability. Hemicryptophytes, characterized by species that survive the dry season in their vegetative state near the ground, were also well-represented. Phanerophytes and geophytes were less frequent, emphasizing the dominance of drought-tolerant forms in this environment.

Capparis decidua was the dominant species in the study area, recorded in all 27 stands surveyed, with a presence value of 100%. It was associated with a variety of other species across different vegetation groups. The composition of these associated species suggests a highly specialized community adapted to the harsh, hyper-arid conditions of the Eastern Desert. The largest life-form categories included chamaephytes (34.4%, representing 22 species) and therophytes (25%, representing 16 species), followed by hemicryptophytes (20.3%, representing 13 species). Phanerophytes and geophytes were less abundant, with phanerophytes making up 17.2% (11 species) and geophytes and parasites contributing only 1.6% (1 species for each one) (Figure 2).

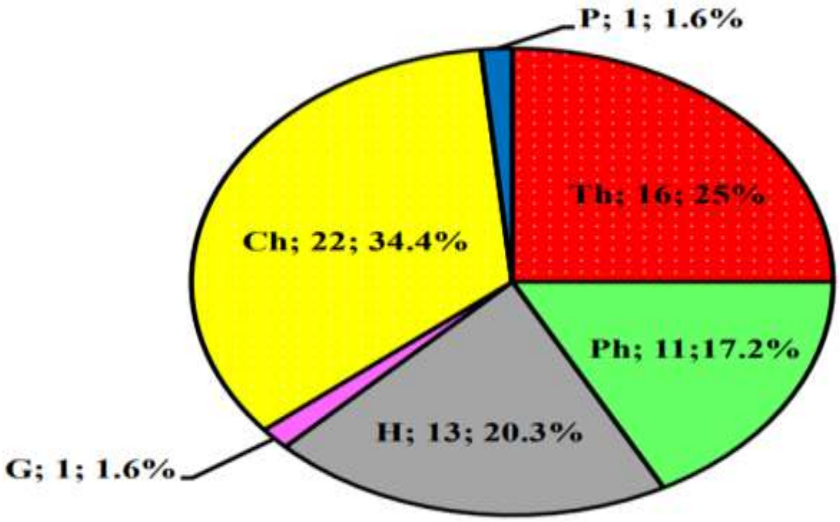

Figure 2: Shows the life forms of the recorded plant species in the study areas.

Chorological Distribution

Chorological analysis revealed that 36 species (56.25%) were of monoregional origin, with the majority belonging to the Saharo-Arabian chorotype, indicative of the dominant biogeographical region in which these species are distributed. A smaller proportion of species (32.8%) were bioregional, and 10.9% were pluri-regional, meaning that these species have a wider distribution, extending beyond the immediate Saharo-Arabian region (Figure 3). The prevalence of Saharo-Arabian species highlights the characteristic flora of the Egyptian Eastern Desert and its connections to similar desert ecosystems across North Africa and the Middle East. The presence of Sudano-Zambezian, Mediterranean, and Irano-Turanian elements further highlights the complex biogeographical patterns within the Eastern Desert flora, where species from various climatic zones coexist, likely due to past climatic shifts and the region's geological history.

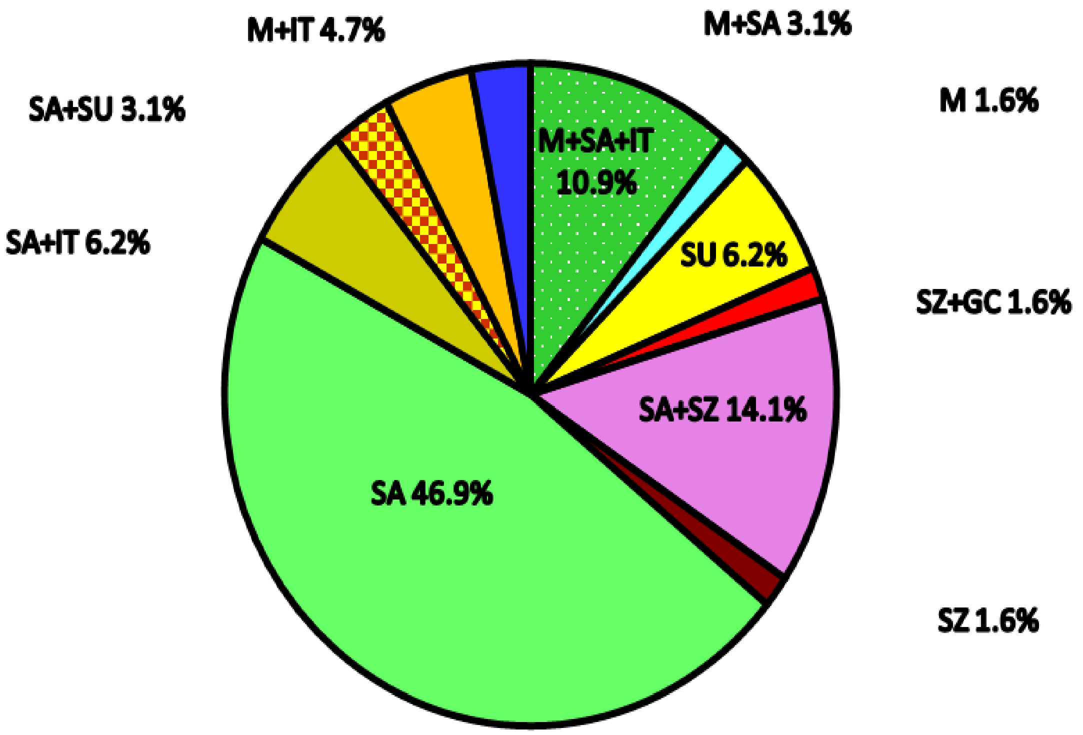

Figure 3. The chorological analysis

Vegetation Classification and Multivariate Analysis

The multivariate analysis, particularly the TWINSPAN (Two-Way Indicator Species Analysis) classification method identified four distinct vegetation groups (A–D), each with specific species associations and environmental conditions (Figure 4 and Tables 2& 3). Group A, the most diverse, consisted of 56 species across 6 stands. *Capparis decidua* and *Zilla spinosa* were the dominant species, while *Senna italica* was co-dominant. This group was characterized by high coarse sand content, magnesium (Mg), and chloride (Cl) concentrations, suggesting a more well-drained soil with moderate nutrient availability.

Group B, comprising 9 stands and 44 species, was dominated by *Capparis decidua* and co-dominated by *Zilla spinosa* and *Vachellia tortilis*. This group was associated with higher clay content, pH, electrical conductivity (EC), total soluble salts (TSS), potassium (K), and calcium (Ca) levels, indicating more compact and nutrient-rich soils. In contrast, Group C, consisting of 8 stands with 30 species, exhibited a different composition, with *Capparis decidua* and *Aerva javanica* as dominant species. This group's soils had higher fine sand, silt, sodium (Na), phosphate (PO_4), carbonate (CO_3), and sulfate (SO_4) levels, with relatively lower potassium (K) content, suggesting slightly less fertile but more saline soils.

Group D, the least diverse with only 21 species in 4 stands, was characterized by the dominance of *Capparis decidua* and *Lobularia arabica*, with *Ochradenus baccatus*, *Pulicaria undulata*, and *Zygophyllum coccineum* as co-dominants. The soils in this group were characterized by the highest pH levels and the lowest concentrations of silt, EC, TSS, calcium, chloride, CO_3 , and SO_4 , indicating less favorable conditions for species requiring high soil moisture and nutrients.

Multivariate Analysis of Vegetation

The multivariate analysis, particularly TWINSPAN (Two-Way Indicator Species Analysis), was used to classify the vegetation into four distinct groups based on floristic composition and soil characteristics (Figure 4 and Tables 2 & 3). These groups are:

- Group A: This group, the most species-rich, included six stands with 56 species. The dominant species were *Capparis decidua* and *Zilla spinosa*, with *Senna italica* as a co-dominant. Soil analysis indicated that this group was characterized by the highest content of coarse sand, magnesium, and chloride, and the lowest levels of clay. These conditions are indicative of well-drained, sandy soils that support a diverse range of xerophytic species.
- Group B: Comprising nine stands and 44 species, this group was dominated by *Capparis decidua*, with *Zilla spinosa* and *Vachellia tortilis* as co-dominants. Soils in this group exhibited higher clay content, pH, electrical conductivity (EC), total soluble salts (TSS), potassium, and calcium compared to Group A, suggesting slightly more fertile and moisture-retentive soils that support a different plant community composition.
- Group C: This group contained eight stands and 30 species, with *Capparis decidua* and *Aerva javanica* as the dominant species. The soils in Group C had the highest concentrations of fine sand, silt, sodium, phosphates (PO_4), carbonates (CO_3), and sulfates (SO_4), yet exhibited the lowest pH and potassium levels. These conditions are associated with more nutrient-rich, but slightly more alkaline soils that favor species with higher salt tolerance.

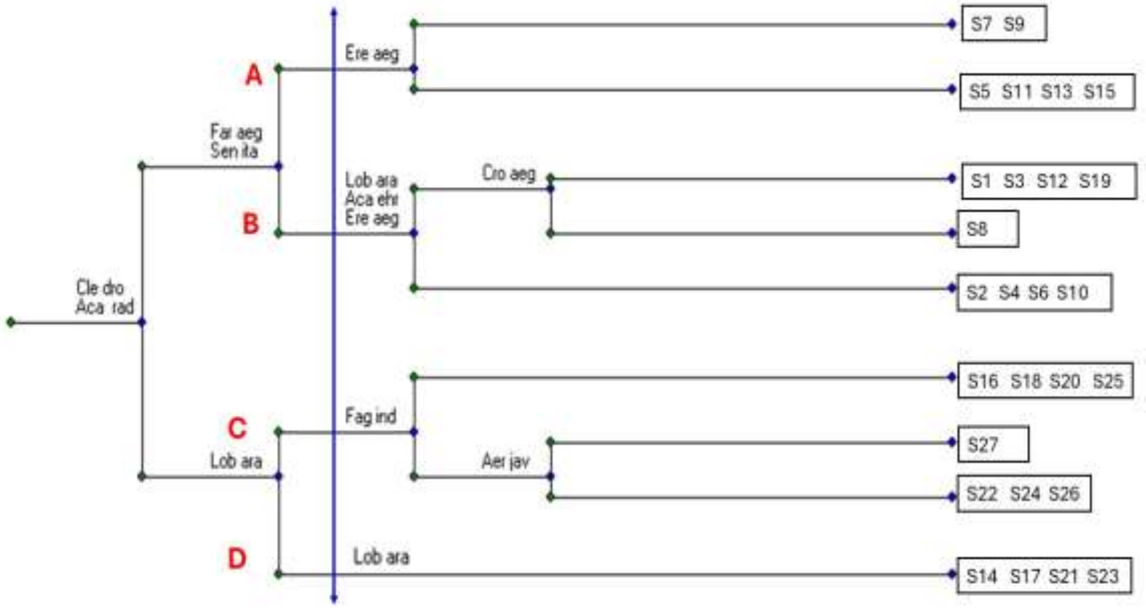

Figure (4): The dendrogram indicating the four TWINSPAN groups (A-D), together with their indicator species resulted from the classification of the 27 stands.

- Group D: The least diverse group, containing four stands and 21 species, was dominated by *Capparis decidua* and *Lobularia arabica*, with *Ochradenus baccatus*, *Pulicaria undulata*, and *Zygophyllum coccineum* as co-dominants. The soil in this group had the highest pH, but low levels of silt, EC, TSS, calcium, chloride, CO_3 , and SO_4 , reflecting the harshest conditions in terms of nutrient availability and water retention.

Table 2: Floristic composition of the vegetation groups (A- D) with the presence values (P%) of each species.

Vegetation groups	**A**	**B**	**C**	**D**
Total number of stands	**6**	**9**	**8**	**4**
Total number of species	**56**	**44**	**30**	**21**
Species present in 4 groups (%)				
Vachellia tortilis (Forssk.) Galasso & Banfi.	**50**	**11.11**	**37.5**	**25**
Arnebia hispidissima (Lehm.) A.D C.	**33.33**	**11.11**	**25**	**50**
Capparis decidua (Forssk.) Edgew.	**100**	**100**	**100**	**100**
Cleome amblyocarpa Baratte. & Murb.	**50**	**11.11**	**37.5**	**50**
Leptadenia pyrotechnica (Forssk.) Decne.	**66.67**	**33.33**	**37.5**	**50**

Ochradenus baccatus Delile	**66.67**	**66.67**	**62.5**	**75**
Pulicaria undulata (L.) C. A. Mey	**50**	**22.22**	**12.5**	**75**
Trichodesma africanum (L.) Sm.	**16.67**	**22.22**	**37.5**	**25**
Zilla spinosa (L.) Prantl	**100**	**88.88**	**50**	**50**
Species present in 3 groups (%)				
Vachellia tortilis (Forssk.) Galasso & Banfi subsp. *raddiana*	**66.67**	**77.78**	**12.5**	
Anchusa aegyptiaca (L.) A.DC.	**16.67**	**22.22**	**37.5**	
Atriplex halimus L.	**33.33**	**22.22**	**12.5**	
Caylusea hexagyna (Forssk.) M.L. Green	**16.67**	**22.22**		**25**
Chrozophora oblongifolia (Delile) A.Juss. ex Spreng.	**33.33**		**12.5**	**25**
Citrullus colocynthis (L.) Schrad.	**33.33**	**22.22**	**25**	
Cleome droserifolia (Forssk.) Delile	**66.66**	**55.55**	**12.5**	
Fagonia glutinosa Delile	**50**	**33.33**	**12.5**	
Fagonia mollis Delile	**50**	**22.22**	**12.5**	
Launaea spinosa (Forssk.) Sch. Bip. ex Kuntze	**33.33**	**44.44**	**50**	
Pergularia tomentosa L.	**16.67**	**11.11**	**12.5**	
Polycarpaea repens (Forssk.) Asch. & Schweinf.	**66.67**	**22.22**		**25**
Pteranthus dichotomus Forssk.	**33.33**	**33.33**	**37.5**	
Retama raetam (Forssk.) Webb		**33.33**	**37.5**	**25**
Rumex vesicarius L.	**33.33**	**11.11**	**25**	
Solenostemma oleifolium (Nectoux) Bullock & E.A. Bruce ex Maire	**16.67**		**37.5**	**25**
Zygophyllum coccineum L.	**50**		**37.5**	**75**
Vachellia ehrenbergiana Hayne	**16.67**	**33.33**		
Aerva javanica (Burm.f.) Juss. ex Schult.		**33.33**	**75**	
Alhagi graecorum Boiss.	**50**	**11.11**		
Anabasis articulata (Forssk.) Moq.	**50**			**25**
Astragalus hamosus L.		**11.11**		**50**
Astragalus vogelii (Webb) Bornm.		**22.22**	**12.5**	
Calligonum polygonoides L.	**16.67**	**22.22**		
Reseda pruinosa Delile	**16.67**		**50**	
Cleome arabica L.	**16.67**	**22.22**		
Crotalaria aegyptiaca Benth.	**16.67**	**44.44**		
Eremobium aegyptiacum (Spreng.) Asch. ex Boiss.	**33.33**	**44.44**		
Erodium glaucophyllum (L.) L'Hér.	**33.33**	**11.11**		
Fagonia arabica L.	**50**	**11.11**		
Fagonia indica Burm.f.			**50**	**25**
Farsetia aegyptia Turra	**66.66**		**37.5**	
Forsskaolea tenacissima L.	**50**			**25**
Haloxylon salicornicum (Moq.) Bunge ex Boiss.	**16.67**	**22.22**		
Hyoscyamus boveanus (Dunal) Asch. & Schweinf.	**50**	**11.11**		
Limonium axillare (Forssk.) Kuntze	**33.33**	**11.11**		
Lobularia arabica (Boiss.) Muschl.		**33.33**		**100**
Panicum turgidum Forssk.	**33.33**	**22.22**		

Reseda alba L.	**16.67**			**75**
Caroxylon gaetulum (Maire) Akhani & Roalson		**44.44**	**12.5**	
Stipagrostis plumosa Munro ex T.Anderson	**33.33**	**11.11**		
Tribulus pentandrus Forssk.	**16.67**	**44.44**		
Zygophyllum album L.	**33.33**	**11.11**		
Species present in 1 group (%)				
Asphodelus tenuifolius Cav.	**50**			
Astragalus sieberi DC.	**33.33**			
Balanites aegyptiaca L.	**50**			
Blepharis ciliaris (L.) B.L.Burtt	**50**			
Capparis spinosa L.	**16.67**			
Senna italica Mill.	**83.33**			
Cornulaca monacantha Delile	**50**			
Lotononis platycarpa (Viv.) Pic.Serm.	**50**			
Lotus hebranicus Brand	**33.33**			
Moringa peregrina (Forssk.) Fiori	**16.67**			
Orobanche crinita Viv.		**11.11**		
Zygophyllum simplex L.	**66.67**			

Detrended Correspondence Analysis (DCA)

The Detrended Correspondence Analysis (DCA) of species composition revealed that the first two axes explained a significant proportion of the variation in species composition, with Axis 1 accounting for 27.9% and Axis 2 explaining 32.9% of the total variance. The separation of the vegetation groups along these axes indicated that soil properties, particularly coarse sand, clay, potassium, and sodium content, played a dominant role in structuring species distribution across the study area. Stands in Groups A and B were located towards the negative end of Axis 1, reflecting the influence of higher nutrient and salinity levels in these groups. On the other hand, stands in Groups C and D were positioned towards the positive end of Axis 1, reflecting the influence of factors such as sodium, fine sand, and sulfate on vegetation composition (Table 3 and Figure 5).

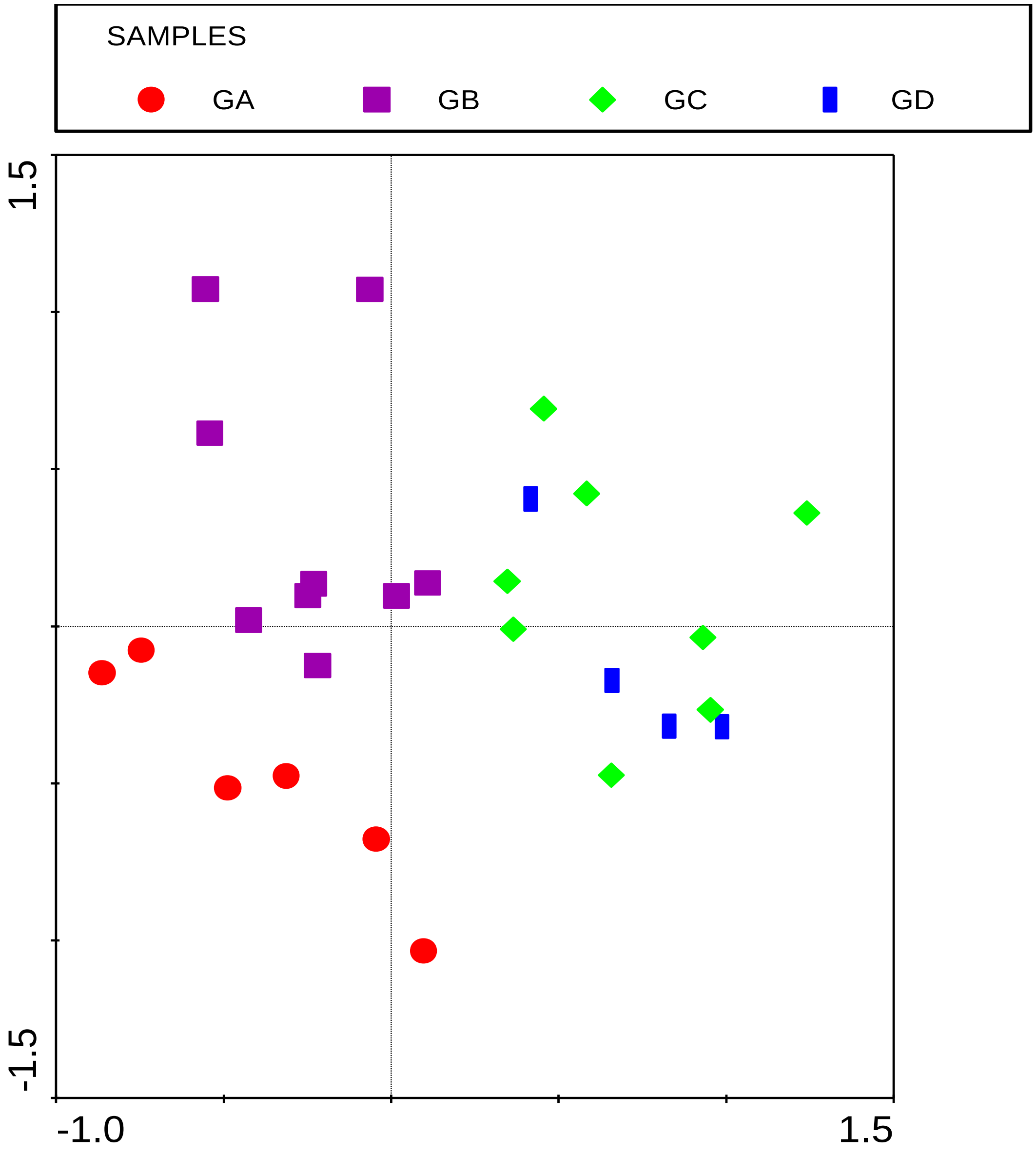

Figure 5: DCA ordination diagram for 27 stands on axes 1 and 2, with the four TWINSPAN groups superimposed.

Soil-Vegetation Relationships

Soil analysis revealed significant variation in the physical and chemical properties across the vegetation groups. Coarse sand content varied significantly ($F = 29.15$, $p < 0.01$) between the groups, with Group A exhibiting the highest levels, suggesting well-drained soils. Clay content also varied significantly ($F = 31.54$, $p < 0.01$), with Group B soils containing the highest proportion of clay, which contributes to water retention and nutrient availability. Electrical conductivity (EC) varied across groups, with Group B soils exhibiting the highest salinity (1188.98 µS/cm), whereas Group D had the lowest EC (641.17 µS/cm), indicating variations in soil salinity that may influence species composition ($F = 7.15$, $p < 0.01$).

Potassium (K) content showed significant differences between the groups ($F = 11.58$, $p < 0.01$), with Group B containing the highest concentration, reflecting soil fertility and plant nutrient availability. Calcium (Ca) also varied significantly, with Group B exhibiting the highest concentration ($F = 7.75$, $p < 0.01$), which is crucial for plant cell wall integrity and growth. The total soluble salts (TSS) and sulfate (SO_4) content also exhibited variation across the vegetation groups, further highlighting the role of soil salinity and nutrient content in structuring plant communities (Table 3).

Soil properties were found to significantly influence plant distribution and diversity in the study area (Table 4 and Figure 6). The Redundancy Analysis (RDA) of soil variables and vegetation composition showed that the first four RDA axes explained 47.1% of the cumulative variation in species composition.

- Axis 1 was strongly influenced by potassium (K) and sulfates (SO_4), with a negative correlation with potassium ($r = -0.599$) and a positive correlation with sulfates ($r = 0.456$). This axis separated the vegetation groups dominated by more salt-tolerant species (such as Groups A and B) from those associated with more alkaline and nutrient-poor conditions (Groups C and D).
- Axis 2 was defined by fine sand and sodium (Na) contents, with sodium showing a positive correlation ($r = 0.708$), suggesting that species in groups C and D are better adapted to soils with higher sodium content and finer textures.

Soil variables such as total soluble salts (TSS), magnesium (Mg), and fine sand played key roles in separating the vegetation groups, supporting the hypothesis that soil texture and salt content are critical factors in determining plant community structure in desert ecosystems.

Table 3: Mean values, standard error, and ANOVA values of the soil variables in the vegetation groups (A-F) of the study area. **= $p < 0.01$.

Soil variables	Vegetation groups				F value	*P*
	A	B	C	D		
Coarse sand	53.43±2.49	28.60±1.22	45.29±2.50	51.95±3.04	29.15**	0.000
Fine sand	15.53±1.03	14.01±1.52	8.86±0.62	9.00±1	7.45	0.001
Silt (%)	17.83±1.64	18.29±0.72	18.37±1.41	16.12±1.35	0.48	0.70
Clay	13.20±1.43	39.10±1.51	27.46±2.17	22.92±3.19	31.54**	0.000
PH	8.40±0.09	8.55±0.06	8.37±0.11	8.55±0.064	1.14	0.351
EC (μS/ cm)	820.52±39.7	1188.98±82.07	814.92±96.48	641.17±106.62	7.15	0.001
TSS	525.13±25.41	701.32±103.37	521.56±61.75	410.32±68.23	2.08	0.130
Na	6.37±0.20	6.17±0.39	6.91±0.15	6.37±0.19	1.34	0.284
K	0.93±0.17	1.24±0.13	0.39±0.048	0.50±0.13	11.58**	0.000
Ca	1.85±0.55	2.97±0.16	1.25±0.35	0.75±0.26	7.75	0.001
Mg (mg.g^{-1} d wt soil)	0.38±0.042	0.28±0.04	0.37±0.078	0.30±0.07	0.71	0.554
Cl	3.23±1.25	2.32±0.25	3.30±1.09	1.27±0.48	0.88	0.462
PO$_4$	0.028±0.014	0.014±0.002	0.092±0.041	0.015±0.003	2.41	0.093
CO$_3$	4.53±0.28	7.84±0.51	8.41±0.37	7.80±0.78	12.59**	0.000
So$_4$	1.37±0.16	1.12±0.08	1.46±0.26	1.10±0.31	0.83	0.462
SR	23.00±5.18	12.89±5.55	10.13±3.18	9.75±9.75	11.32**	0.000
H'	3.11±0.23	2.48±0.41	2.27±0.33	2.26±0.24	8.75**	0.000

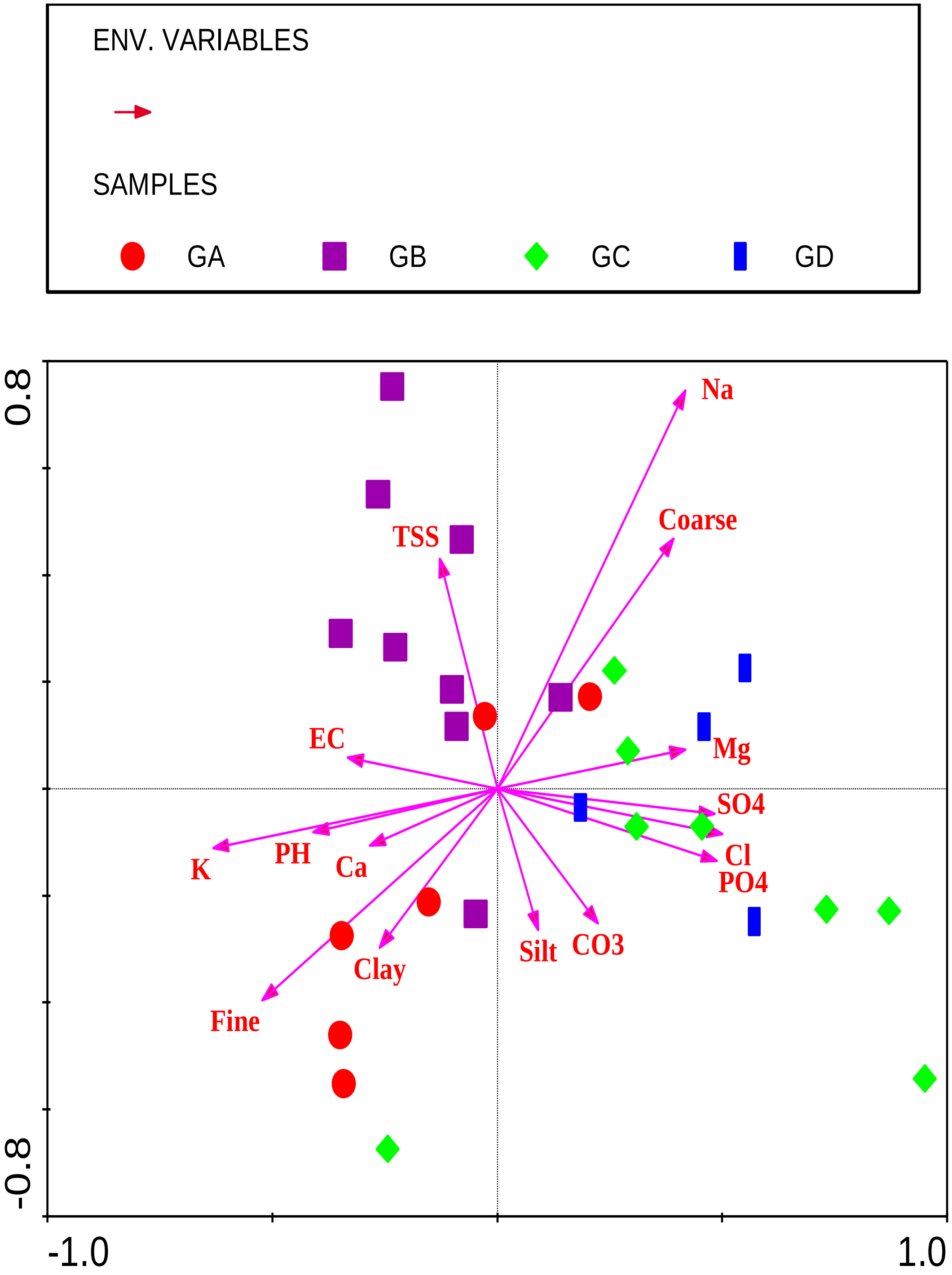

Figure 6: Ordination biplot yielded by Redundancy Analysis (RDA) of the 27 stands with their TWINSPAN groups and soil variables.

Species Diversity Indices

The species richness and Shannon-Wiener diversity index (H’) were significantly higher in Group A, which exhibited the highest species richness (23.00 ± 5.18 species per stand) and a high diversity index (H’ = 3.11 ± 0.23). This indicates a rich and varied plant community structure in Group A. Conversely, Group D had the lowest diversity indices, with the lowest species richness (21.00 ± 3.18 species per stand) and a Shannon-Wiener index of 2.26 ± 0.24, reflecting lower ecological complexity and diversity in this group (Table 3).

DISCUSSION

Ecological Significance of *Capparis decidua*

The current study provides critical insights into the ecological and phytosociological patterns of *Capparis decidua* in the hyper-arid Wadi Tundoub, emphasizing its role as a keystone species in desert ecosystems. The dominance of *Capparis decidua* in all vegetation groups indicates its exceptional adaptability to hyper-arid environments. Its resilience to harsh conditions is attributable to several physiological adaptations, including deep root systems, leafless photosynthetic stems, and efficient water-use strategies [1]. These traits enable the species to occupy various soil types, from coarse sandy soils to clay-dominated substrates, as seen in the current study. This versatility positions *Capparis decidua* as a cornerstone species in desert ecosystems, providing shelter, food, and stabilization of soil structure [2].

Recent studies have emphasized the plant's ability to thrive in disturbed or degraded landscapes, such as those impacted by overgrazing or climate change [10]. Its presence enhances ecosystem stability by reducing soil erosion and facilitating nutrient cycling, which benefits co-occurring species like *Zilla spinosa* and *Aerva javanica*. This underscores its ecological role as a foundation species, vital for maintaining biodiversity in arid regions [9,3].

Floristic Composition and Community Structure

The study area’s floristic diversity, comprising 64 species from 22 families, reflects the adaptation of plant communities to hyper-arid conditions. The dominance of chamaephytes and therophytes among life forms aligns with their ability to minimize water loss and endure prolonged dry seasons [30]. This life form spectrum is typical of desert vegetation and parallels findings from other arid environments, such as the Atacama Desert [31] and Saudi Arabia [32].

Vegetation groups identified by TWINSPAN analysis highlight distinct community structures influenced by soil properties. Group A, characterized by sandy soils with low nutrient retention, supports the growth of xerophytic species with high drought tolerance. In contrast, Group B, associated with clay-rich soils and higher nutrient availability, exhibits greater floristic richness. These results align with studies that link vegetation distribution to soil moisture and texture gradients [25,13].

Soil-Vegetation Relationships

The multivariate analyses, particularly Redundancy Analysis (RDA), revealed significant correlations between soil factors and species distribution. For instance, coarse sand and potassium content were influential in shaping vegetation patterns, with coarse-textured soils favoring drought-tolerant plants and nutrient-rich soils supporting higher species diversity. These findings are consistent with studies from the Eastern Desert and other arid regions, which highlight the interplay of soil texture, salinity, and nutrient availability in structuring plant communities [33,34].

Conservation Implications

The increasing anthropogenic pressures on desert ecosystems, including overharvesting of *Capparis decidua*, urbanization, and quarrying, threaten biodiversity and ecosystem function. These activities disrupt natural vegetation patterns, reduce species richness, and exacerbate soil degradation [12,35]. To mitigate these impacts, conservation strategies must prioritize the sustainable use of *Capparis decidua* and its habitat.

Community-based conservation programs that integrate traditional ecological knowledge with modern land management practices offer promising solutions. For instance, the use of Capparis decidua in reforestation projects and soil stabilization initiatives not only aids in habitat restoration but also supports local livelihoods through the sustainable harvest of its fruits and medicinal products [1,2].

Broader Ecological Relevance

The findings from Wadi Tundoub contribute to a growing body of research highlighting the ecological importance of wadis as biodiversity hotspots in arid regions. These ephemeral watercourses act as refugia for diverse flora and fauna, providing microhabitats that buffer against climatic extremes. This study emphasizes the need to conserve such ecosystems, particularly in the face of accelerating climate change, which is expected to intensify desertification and habitat loss [36,11].

Methodological Insights and Future Directions

This study's integration of TWINSPAN and RDA methods offers a robust approach to understanding vegetation dynamics concerning environmental gradients. However, further research is needed to explore the genetic and physiological mechanisms underlying *Capparis decidua*'s adaptability. Long-term monitoring of vegetation and soil properties would provide insights into the impacts of climate variability and human activity on desert ecosystems.

Additionally, expanding the study to include comparative analyses with other hyper-arid regions, such as the Namib or Kalahari Deserts, could elucidate broader patterns of xerophytic adaptation and ecosystem resilience. Advanced remote sensing and Geographic Information System (GIS) technologies could enhance the spatial analysis of vegetation and improve conservation planning.

CONCLUSION

This study highlights the ecological significance of *Capparis decidua* in Wadi Tundoub, demonstrating its resilience to extreme aridity and its role as a keystone species in desert ecosystems. The plant's ability to thrive across various soil types underscores its adaptive strategies in harsh environments. The floristic composition, which includes 64 species, reflects the biodiversity of desert wadis, influenced by soil properties such as texture and nutrient content. However, anthropogenic pressures threaten this delicate balance, emphasizing the need for conservation efforts. Sustainable management practices and further research are essential to preserving *Capparis decidua* and the biodiversity of Egypt’s Eastern Desert.

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